

Double sampling may improve the efficiency of litterfall estimates¹

Mary Dellenbaugh, Mark J. Ducey, and James C. Innes

Abstract: The effort required for an extensive litterfall measurement campaign can be prohibitive. We propose a double sampling approach, in which a large set of traps is used in each stand to estimate total litterfall, and only a subset of these traps is sorted to the relevant components. We examine its feasibility using data from a regional litterfall study of eastern white pine (*Pinus strobus* L.), in which the variables of interest were biomass of foliar litterfall from pine and nitrogen content of foliar litterfall from all vegetation. Double sampling was more efficient than simple random sampling but only if every trap received a rapid presorting to remove twigs and cones. The optimal strategy when pine foliar litterfall biomass was the target variable was to conduct full sorting on 33% of the traps. When foliar litterfall N was the target, sorting only 20% of the traps was optimal. Holding time costs constant, the variance of estimated pine foliar litterfall biomass could be reduced by 18%, whereas that for foliar litterfall N could be reduced by 49%. Alternately, when variance was held constant, the time cost could be reduced by 17% for pine foliar litterfall biomass or 44% for foliar litterfall N.

Résumé : L'effort requis pour effectuer une importante campagne de mesure de chute de litière peut s'avérer prohibitif. Nous proposons une approche à échantillonnage double selon laquelle un grand nombre de trappes sont utilisées dans chaque peuplement pour estimer la chute de litière totale et les composantes pertinentes sont triées dans seulement quelques unes de ces trappes. Nous avons estimé la faisabilité de cette approche à l'aide des données d'une étude régionale de chute de litière du pin blanc (*Pinus strobus* L.) dans laquelle les variables d'intérêt étaient la biomasse foliaire du pin dans la chute de litière et la teneur en N foliaire de toute la végétation dans la chute de litière. L'échantillonnage double était plus efficace qu'un seul échantillonnage aléatoire mais seulement si chaque trappe subissait un tri préliminaire rapide pour enlever les rameaux et les cônes. Lorsque la biomasse foliaire du pin dans la chute de litière était la variable ciblée, la stratégie optimale consistait à effectuer le tri complet de 33 % des trappes. Lorsque le contenu en N foliaire dans la chute de litière était ciblé, le tri de seulement 20 % des trappes était la solution optimale. Si les coûts de période étaient gardés constants, la variance de la biomasse estimée des aiguilles de pin dans la chute de litière pouvait être réduite de 18 % tandis que celle du contenu en N foliaire dans la chute de litière pouvait être réduite de 49 %. Inversement, si la variance était maintenue constante, les coûts de période pouvaient être réduits de 17 % dans le cas de la biomasse foliaire du pin dans la chute de litière ou de 44 % dans le cas de N foliaire dans la chute de litière.

[Traduit par la Rédaction]

Introduction

Litterfall sampling has formed an important component of a wide variety of ecological investigations in a variety of vegetated systems. Litterfall is often studied in its own right as an important component of carbon and nutrient cycles (e.g., Magill and Aber 1998). It is also widely used to evaluate the

leaf area or biomass of forested canopies, either as part of a forest growth study or to determine canopy properties affecting energy exchange (e.g., Neumann et al. 1989; Chason et al. 1991; Burnham 1997). However, litterfall measurement is notoriously time consuming, restricting its utility to studies of limited scope and sample size.

Litterfall sampling in forests is reasonably straightforward, at least conceptually. Typically, a number of "traps" are placed within each study area (usually a plot or stand). Material falling into the traps is collected periodically and taken to the laboratory where it is sorted. Sorting is almost always done by general physical categories (e.g., twigs, foliage, or seeds) and may be taken to species or some other taxonomical or functional group for some or all categories. The collected, sorted material is then expanded back to a per unit area basis by multiplying by the reciprocal of trap size. When the placement of traps within the study area is random, this is a form of simple random sampling. Finotti et al. (2003) studied the number of traps required when sim-

Received 28 April 2006. Accepted 17 October 2006. Published on the NRC Research Press Web site at cjfr.nrc.ca on 5 June 2007.

M. Dellenbaugh, M.J. Ducey,² and J.C. Innes.³ Department of Natural Resources, University of New Hampshire, 215 James Hall, Durham, NH 03824, USA.

¹Contribution No. 2335 of the New Hampshire Agricultural Experiment Station, Durham, N.H.

²Corresponding author (e-mail: mjducey@cisunix.unh.edu).

³Present address: USDA Forest Service, Sierra Nevada Research Center, 2121 2nd Street, Suite A-101, Davis, CA 95616, USA.

ple random or systematic sampling was used and found that only five traps were needed at their study site. They noted that the recommendation of ≥ 20 traps made by other authors (e.g., Proctor 1983; Stocker et al. 1995) would require significant field and laboratory effort and suggested that appropriate consideration of sampling theory, informed by data, might provide better site- and study-specific guidance.

Typically, all of the material collected is sorted, and the sorting process represents the majority of the effort and cost associated with a litterfall campaign. We hypothesized that a properly designed subsampling strategy might eliminate much of this effort and cost with minimal loss in accuracy or, conversely, might improve estimates without any increase in effort or cost. Formally, the approach we propose is a type of double sampling or two-phase sampling (Thompson 1992). In this approach, a first-phase sample (the complete set of traps in a stand) is measured without sorting to determine total mass of litterfall. A second-phase subsample (a randomly chosen subset of the traps) is measured in more detail to determine the value of a target variable or variables per unit total mass.

Double sampling has been proposed in a variety of ecological monitoring contexts, most notably in sampling the number or biomass of live and dead trees (Gregoire et al. 1995; Williams 2001; Ringvall et al. 2001). It has also been used successfully in sampling fine fuels on the forest floor (Fule and Covington 1994). However, there are no published accounts of its formal use in litterfall sampling.

Here, we present an analysis of litterfall data from a field study in forest stands dominated by eastern white pine (*Pinus strobus* L.), in which the primary variable of interest is biomass per acre (1 acre = 0.405 ha) of pine foliar litterfall. We also examine the situation when nitrogen content of foliar litterfall is a variable of interest. We illustrate the calculations involved in double sampling and test whether double sampling can in fact improve the efficiency of sampling in an extensive campaign.

Methods

Field and laboratory data

The data presented here come from a regional study of biomass production in managed stands dominated by eastern white pine located in southern New Hampshire, USA. In July 2000, litterfall collection was initiated on a subset of the study plots (Innes 2001; Innes et al. 2005). The plots are located between $42^{\circ}59'N$ and $43^{\circ}28'N$ and between $71^{\circ}39'W$ and $70^{\circ}55'W$. These twelve 0.08 ha circular plots represent a broad range of site conditions and forest structures. Several of the stands possess a diverse and well-developed subcanopy and understory including species such as eastern hemlock (*Tsuga canadensis* (L.) Carr.), northern red oak (*Quercus rubra* L.), red maple (*Acer rubrum* L.), American beech (*Fagus grandifolia* Ehrh.), witch-hazel (*Hamamelis virginiana* L.), maple leaf viburnum (*Viburnum acerifolium* L.), and low-bush blueberry (*Vaccinium angustifolia* Ait.).

Six litterfall traps were located uniformly at random within each of the 12 plots. On 10 plots, the traps were 1 m²; on 2 plots where high tree density precluded the use

of large traps, the traps were 0.5 m². All traps were constructed of aluminum window screen on a lightweight lumber frame and were located at the ground surface. Litterfall collection was made during the snow-free season on an approximately monthly basis, with more frequent collection during peak autumn litterfall. The litter from each trap was placed in a large labeled paper bag on site. After collection, the material was dried at 60–65 °C for at least 24 h to arrest decomposition. The litter was then sorted into nine species-component categories and placed in small labeled paper bags. Before final weighing, the material was again dried for at least 24 h at 60–65 °C to remove moisture accrued during storage. Data reported here represent the first calendar year of collection at each site.

Statistical analysis

In a typical litterfall campaign, each trap would be treated as an observation in a simple random sample for the purposes of estimating litterfall at a plot. Suppose the litter has been sorted into M components and denote the dry mass of component m in trap i as x_{im} . Further, let each component contribute c_m units per unit dry mass toward some variable of interest Y , which is expressed per square metre. The c_m may represent concentrations if, for example, Y is nutrient content per unit area, or it may represent binary indicator variables, if Y is the dry mass of one or more components per unit area. For the purposes of the present study, we assume the c_m units are known. Let y_i represent the estimate of Y formed considering trap i in isolation, namely:

$$[1] \quad y_i = \frac{1}{a} \sum_{m=1}^M c_m x_{im}$$

where a is the trap area (m²). Then:

$$[2] \quad \bar{y} = \frac{1}{n} \sum_{i=1}^n y_i$$

$$s_{\bar{y}}^2 = \frac{1}{n(n-1)} \sum_{i=1}^n (y_i - \bar{y})^2$$

are the familiar, design-unbiased estimators for Y and for the variance of \bar{y} or its squared standard error (e.g., Thompson 1992). Usually, the litterfall trap locations are taken without replacement (i.e., traps cannot overlap), but the total area of the traps is negligible compared with the plot or stand area, so we can ignore the finite population correction in the variance estimate. The use of eqs. 1 and 2 requires that we measure x_{im} for every component in every plot; this requires tedious sorting of a large volume of material.

By contrast, in a double-sampling approach, only a random subsample n_s of the n total traps would be sorted, and the remainder of the traps would remain unsorted. The full set of n traps is the phase I set; the subsample of n_s traps represents phase II. In that case, our only measurement for the unsorted phase I traps would be the total dry mass, taken as a single measurement after final drying of the unsorted litter. The total dry mass can easily be obtained immediately before sorting for the sorted traps if the material is thoroughly dried first or with little loss of accuracy by summing

the components after sorting and final drying (i.e., $x_{i*} = \sum_m x_{im}$). We might expect a trivial loss of very fine particles in the sorting process but would expect this to be negligible. We also consider the possibility that a rapid preliminary sorting might remove particularly problematic components, such as twigs and branches, from the phase I traps before the determination of total mass; this would change the laboratory procedure and the definition of x_{i*} but would not change the mathematics to follow.

An estimate for Y in the double-sampling case (specifically, ratio-of-means double sampling) can be formed as

$$[3] \quad \begin{aligned} \hat{y}_{\text{dsr}} &= \hat{r}\bar{x} \\ \hat{r} &= \frac{\sum_{n_s} y_i}{\sum_{n_s} x_i} = \frac{\bar{y}}{\bar{x}} \\ \bar{x} &= \frac{1}{n} \sum_n x_{i*} \end{aligned}$$

where the subscript dsr denotes double sampling with a ratio estimator. An estimator of the variance of \hat{y}_{dsr} is (de Vries 1986; Shiver and Borders 1996):

$$[4] \quad s_{\hat{y}_{\text{dsr}}}^2 = \frac{f}{n_s} + \frac{g}{n} + h$$

where

$$\begin{aligned} f &= s_y^2 + \hat{r}^2 s_x^2 - 2\hat{r}s_{xy} \\ g &= 2\hat{r}s_{xy} - \hat{r}^2 s_x^2 \\ h &= -\frac{s_y^2}{A/a} \end{aligned}$$

where A is the total area of the stand or plot (m^2); the term h relates to the finite population correction and can almost always be ignored in litterfall sampling. The sample variance of x , s_x^2 , is calculated from the x_{i*} values on the full phase I sample of n traps; the sample variance of y , s_y^2 , is calculated from the n_s traps in the sorted phase II subsample; and the sample covariance of x and y , s_{xy} , is also calculated from the n_s phase II traps.

We evaluated two different scenarios to determine the impact of a double-sampling strategy on a litterfall campaign relative to a simple random sampling strategy. One scenario involves holding the total cost of the campaign fixed and identifying the optimal ratio of n_s/n . We consider cost here primarily in terms of technician time, although financial cost (including costs for processing nutrient samples) could also be addressed using the same methodology. Let t be the cost of collecting and minimally processing a litterfall trap to observe x_i , and let t_s be the additional cost to obtain y_i . Then the optimal ratio of n_s to n is (Sukhatme and Sukhatme 1970; Cochran 1977; Thompson 1992):

$$[5] \quad p = \sqrt{\frac{t}{t_s} \left(\frac{s_r^2}{s_y^2 - s_r^2} \right)}$$

where

$$s_r^2 = \frac{1}{n_s} \sum_{n_s} (y_i - \hat{r}x_i)^2$$

Solving for the n and n_s that provide equal cost to n_{srs} (the sample size for the original simple random sample), then substituting into eq. 4, provides an estimate of the reduction in variance that could have been obtained relative to simple random sampling. Note that, because $n_s = pn$, the total cost of the sample is $nt + pnt_s$ in double sampling and $n_{\text{srs}}(t + t_s)$ in simple random sampling. Using p as calculated from eq. 5 and setting $nt + pnt_s = n_{\text{srs}}(t + t_s)$, solution for n is straightforward, and n_s follows immediately.

We also evaluated the scenario in which the variance of the double sample estimator is held equal to the variance from simple random sampling, and gains in efficiency were translated into cost savings. Equations for n and n_s in this case are given by Oderwald and Jones (1992). The ratio $(tn + t_s n_s)/[(t + t_s)n_{\text{srs}}]$ provides a measure of the cost savings with double sampling. Recognizing that cost figures are often approximate, Oderwald and Jones (1992) also show that double sampling always provides cost savings for fixed variance, whenever the cost ratio $k = (t + t_s)/t$ meets the following criterion:

$$[6] \quad k > k_{\text{crit}} = \frac{B^2}{2\rho B - 1}$$

where ρ is the correlation coefficient between x and y and

$$B = \frac{\bar{x}}{\bar{y}} \sqrt{\frac{s_y^2}{s_x^2}} = \frac{\text{CV}_y}{\text{CV}_x}$$

Tabulation of k_{crit} provides an indication of when double sampling would be advantageous, even if the costs associated with measurement cannot be determined exactly in advance.

We evaluated double sampling using two different definitions of Y :

1. Y was defined as the dry mass of pine foliar litterfall, setting $c_m = 1$ for the pine foliage component and $c_m = 0$ for all others. Such a definition might be appropriate when the litterfall campaign supports a study of the production ecology of the dominant overstory trees or when overstory leaf area is a prime concern for surface energy budgets.
2. Y was defined as the nitrogen content of all foliar litterfall, setting $c_m = 0$ for nonfoliar components, such as twigs, cones, seeds, and undifferentiable fine material, and using representative concentrations from the literature for all sorted foliar litterfall components. White pine litterfall N concentration was taken as 0.63% on a dry-mass basis (Delaney et al. 1996), whereas eastern hemlock litterfall N concentration was taken as 0.82% (Finzi et al. 1998). A wide range of litterfall N values have been reported for hardwood species in this region; we used the yellow birch (*Betula alleghaniensis* Britt.) litterfall N concentration of 1.18% reported by Magill and Aber (1998), because it represented a value substantially different from the white pine or hemlock values. Increasing the variability of the concentrations would tend to make double sampling less efficient; hence, the

use of these values gives a conservative estimate of the effectiveness of the technique. These concentrations are not intended to be exact for the study sites reported here but are intended merely to indicate what the performance of double sampling would be in a formal study of nutrient cycling in litterfall.

We also considered two different procedures, leading to different operational definitions of x :

1. Material from unsorted phase I traps (i.e., traps not among the n_s phase II traps) is dried and weighed in bulk, without any sorting whatsoever. In this case, x is the total litterfall mass.
2. Material from unsorted phase I traps receives a presorting to remove twigs and cones, which might contribute unduly to noise in the relationships between x and y . In this case, x is the total litterfall mass less the mass of the twigs and cones.

Time requirements to process litterfall samples can be highly variable, depending on the skill of the technician and the amount and complexity of material in the trap. The minimal time (t) to process a trap includes collection of material in the field; handling for postcollection drying; final drying, weighing, and archiving or disposing of sample material; and tabulation, entry, and checking of data. The additional time required to observe Y , t_s , is the time required to sort the sample to final components. Experience in our laboratory suggests that, when no presorting is conducted, t_s ranges from $6t$ to $10t$, so that k ranges from 7 to 11. When presorting is conducted, t is increased by the time required for presorting. However, because presorting is not required for those traps that will be sorted to final components, the presorting time can be deducted from t_s . In this case, t_s ranges from $4t$ to $7t$, so that k ranges from 5 to 8. For the purposes of this paper, we used $k = 8$ when no presorting was conducted, and $k = 6$ when presorting was included.

Results and discussion

Estimates and their standard errors, as computed using simple random sampling, for total litterfall biomass, pine foliar biomass, and total foliar litterfall N are shown in Table 1. All three quantities varied by a factor of three to four across the study stands. Given this range of variability, six litterfall traps appears to a reasonable number for estimating these three quantities at the plot scale. Pooled coefficients of variation for the estimate were 9.7% for total litterfall biomass, 8.9% for pine foliar biomass, and 10.8% for foliar litterfall N.

Optimization of the double-sampling approach, treating the time cost as fixed but minimizing overall variance (following Sukhatme and Sukhatme 1970), is shown in Table 2. In general, double sampling does not improve the variance unless presorting of twigs and cones is conducted. However, if twigs, cones, and coarse woody material are presorted from the otherwise unsorted phase I traps, double sampling is nearly always successful. Presorting twigs, cones, and other coarse material eliminates a substantial source of variance that is not correlated with foliar mass or N content. With pine foliar litterfall as the primary target variable for the campaign, a strategy of fully sorting only one-third of the total trap number yields a 20% reduction in variance.

Table 1. Estimates for total litterfall, white pine foliar litterfall, and total foliar litterfall N (g/m^2) for the 12 study sites.

Site	Total litterfall	White pine foliar litterfall	Total foliar litterfall N
HP19	563.9 \pm 62.9	166.9 \pm 14.0	2.74 \pm 0.33
HP21	449.9 \pm 36.1	138.6 \pm 13.1	1.67 \pm 0.16
HP33	345.0 \pm 31.1	100.5 \pm 10.0	1.86 \pm 0.05
HP34	542.3 \pm 33.7	190.0 \pm 10.0	2.51 \pm 0.15
HP36	750.5 \pm 64.9	258.0 \pm 23.1	2.67 \pm 0.24
KFA	634.0 \pm 81.7	343.1 \pm 33.8	2.37 \pm 0.19
MA-1	288.3 \pm 13.2	146.4 \pm 15.8	1.27 \pm 0.06
MA-3	211.4 \pm 22.9	123.9 \pm 6.7	0.85 \pm 0.05
MY-KEN2	353.2 \pm 34.3	185.5 \pm 4.2	1.27 \pm 0.03
MYA-4	626.7 \pm 72.5	362.0 \pm 41.9	2.65 \pm 0.28
WWC	630.5 \pm 60.3	250.1 \pm 20.2	3.52 \pm 0.36
WWF	419.4 \pm 34.0	152.3 \pm 21.2	2.09 \pm 0.20

Note: Six litterfall traps were employed at all sites. Values are means \pm SEs.

With total litterfall N as the primary target variable, fully sorting only one-fifth of the total trap number yields a 49% reduction in variance. However, note that the Sukhatme and Sukhatme (1970) optimization maintains a constant total time cost, so that the reduction in number of fully sorted traps is compensated by a considerable increase in the number of traps that receive only a presorting. In the cases examined here, the total number of traps in a typical (i.e., median) situation would increase from 6 to 16–20. It is possible that the increase in sheer volume of material to be dried might overwhelm all but the best-equipped labs in such a case. Fortunately, the optimal ratio of n_s/n can also be applied to a reduced total number of traps to ensure an optimal time cost–variance tradeoff. One simply multiplies the optimal ratio, as calculated using eq. 5, by the desired value of n to obtain n_s . However, it is important to note that, as n declines, the variance of the estimates will inevitably increase.

By contrast, optimization of the double-sampling problem following Oderwald and Jones (1992) takes the variance of the result as fixed and minimizes the overall time cost. The results of our analysis using this method are shown in Table 3. As before, double sampling without presorting to remove twigs, cones, and woody material is largely ineffective. However, when presorting is conducted, typical costs are reduced by 17% when pine foliar litterfall biomass is the target variable and by 44% when total foliar litterfall N is the target variable. The total number of traps in both cases is typically around 10, with considerable variability in the number of traps for full sorting. In two cases when foliar litterfall N was the target variable, the optimal result was to sort only one trap; we note that, in this case, calculation of a standard error from the resulting data would be impossible. Sorting a minimum of two traps seems reasonable for most practical work. The relatively low values of k_{crit} for both variables when litter has been presorted indicate that double sampling will be more efficient even if k differs substantially from the range of 6–8 employed in this analysis.

Whether the fixed time cost (Table 2) or fixed variance (Table 3) approach is used, the efficiency of double sampling does appear to be associated with stand characteristics

Table 2. Double-sampling strategies that provide equal time cost to a simple random sample of six litterfall traps but minimize the sample variance.

Site	Target: pine foliage								Target: foliar litter N							
	Presorting: none				Presorting: twigs and cones				Presorting: none				Presorting: twigs and cones			
	Optimal n_s/n	n	n_s	Variance ratio	Optimal n_s/n	n	n_s	Variance ratio	Optimal n_s/n	n	n_s	Variance ratio	Optimal n_s/n	n	n_s	Variance ratio
HP19	0.576	6	6	1.00	0.307	11	5	0.79	0.217	20	4	0.65	0.140	21	3	0.47
HP21	0.750	6	6	1.00	0.475	11	5	0.96	1.000	6	6	1.00	0.251	16	4	0.70
HP33	1.000	6	6	1.00	0.516	11	5	0.98	1.000	6	6	1.00	1.000	6	6	1.00
HP34	1.000	6	6	1.00	0.150	21	3	0.49	1.000	6	6	1.00	0.125	21	3	0.44
HP36	0.207	20	4	0.63	0.188	16	4	0.57	0.402	13	5	0.93	0.164	21	3	0.52
KFA	0.587	6	6	1.00	0.252	16	4	0.70	1.000	6	6	1.00	0.213	16	4	0.63
MA-1	0.509	6	6	1.00	0.355	11	5	0.85	1.000	6	6	1.00	0.285	16	4	0.46
MA-3	1.000	6	6	1.00	0.654	6	6	1.00	1.000	6	6	1.00	0.122	21	3	0.43
MY-KEN2	1.000	6	6	1.00	0.671	6	6	1.00	1.000	6	6	1.00	0.458	11	5	0.95
MYA-4	0.158	20	4	0.51	0.144	21	3	0.48	0.435	13	5	0.96	0.190	16	4	0.58
WWC	0.104	27	3	0.37	0.286	16	4	0.46	0.733	6	6	1.00	0.215	16	4	0.63
WWF	1.000	6	6	1.00	0.983	6	6	1.00	0.465	13	5	0.97	0.344	11	5	0.84
Median	1.000			1.00	0.331			0.82	1.000			1.00	0.201			0.51

Note: Optimal n_s/n is the optimal fraction of traps to receive full sorting; n and n_s indicate the total number of traps and number of sorted traps, respectively, that minimizes variance without exceeding the original time cost subject to the constraint that only whole numbers of traps can be employed. Variance ratio is the ratio of the variance that could be achieved using double sampling to the variance achieved using simple random sampling.

Table 3. Double-sampling strategies that provide equal sampling variance to simple random sampling with six litterfall traps but minimize the time cost.

Site	Target: pine foliage								Target: foliar litter N							
	Presorting: none				Presorting: twigs and cones				Presorting: none				Presorting: twigs and cones			
	n	n_s	Cost ratio	k_{crit}	n	n_s	Cost ratio	k_{crit}	n	n_s	Cost ratio	k_{crit}	n	n_s	Cost ratio	k_{crit}
HP19	6	6	1.00	6.2	10	4	0.83	1.62	11	3	0.67	1.42	10	1	0.42	1.12
HP21	6	6	1.00	23.2	9	5	0.94	2.75	6	6	1.00	na	10	3	0.69	1.40
HP33	6	6	1.00	na	8	5	0.92	3.18	6	6	1.00	na	6	6	1.00	na
HP34	6	6	1.00	na	10	2	0.56	1.14	6	6	1.00	na	9	1	0.39	1.09
HP36	11	3	0.67	1.4	10	2	0.56	1.22	10	5	0.94	2.76	10	2	0.56	1.17
KFA	6	6	1.00	6.6	10	3	0.69	1.41	6	6	1.00	na	10	2	0.56	1.29
MA-1	6	6	1.00	4.4	10	4	0.83	1.87	6	6	1.00	na	10	3	0.69	1.53
MA-3	6	6	1.00	na	6	6	1.00	5.48	6	6	1.00	na	9	1	0.39	1.09
MY-KEN2	6	6	1.00	na	6	6	1.00	5.90	6	6	1.00	na	9	5	0.94	2.60
MYA-4	11	2	0.52	1.2	10	2	0.56	1.13	9	5	0.92	3.17	10	2	0.56	1.23
WWC	10	1	0.35	1.1	10	3	0.69	1.53	6	6	1.00	19.3	10	2	0.56	1.29
WWF	6	6	1.00	na	6	6	1.00	169.6	9	5	0.92	3.6	10	4	0.83	1.81
Median			1.00	14.7			0.83	1.75			1.00	na			0.56	1.29

Note: The total number of traps and number to sort are given by n and n_s , respectively. Cost ratio is the time cost of the optimal double sampling strategy as a fraction of the time cost for simple random sampling. The critical value of k , the ratio of time cost for a fully sorted trap to time cost for a presorted or unsorted trap, is given in k_{crit} . If k_{crit} is shown as not applicable (na), the relationships between variables prevent effective use of double sampling, and k_{crit} is treated as infinity for calculating the median among sites.

when foliar biomass is the variable of interest. For example, the variance ratio for white pine foliage, when twigs and stems are presorted, is negatively correlated with white pine foliage biomass ($r = -0.73$, $p = 0.0076$). This suggests that double-sampling is most effective when foliar litterfall is highest. However, no similar simple correlation was found in this study when total litterfall N was the variable of interest.

Conclusion

Double sampling with ratio estimation can improve the efficiency of litterfall estimates, provided all traps are presorted to remove bulky materials that do not contribute to the quantities of interest (in this case, twigs and cones). Double sampling was more efficient for N cycling in litterfall than for the foliar biomass of the dominant species in this study. An optimal double sampling strategy involved the full sorting of only one-third of traps when the target variable was the foliar biomass of eastern white pine, and one-fifth of the traps when the target variable was the total N in foliar litterfall. These results are encouraging, but the optimal ratios will undoubtedly vary across forest types and for different target variables. We would encourage other researchers with existing litterfall data sets to examine the optimal ratios for their situations and variables of interest and to share those results to see if general patterns to guide future litterfall studies might emerge.

Acknowledgements

Gregory Jordan, Steven Roberge, and Robert Kenning assisted in the collection and sorting of litterfall data. We thank Ken Desmarais, Ethan Howard, and James Barrett for maintaining several of the permanent plots used in this study.

References

- Burnham, R.J. 1997. Stand characteristics and leaf litter composition of a dry forest hectare in Santa Rosa National Park, Costa Rica. *Biotropica*, **29**: 384–395. doi:10.1111/j.1744-7429.1997.tb00034.x.
- Chason, J.W., Baldocchi, D.D., and Huston, M.A. 1991. A comparison of direct and indirect methods for estimating forest canopy leaf area. *Agric. For. Meteorol.* **57**: 107–128. doi:10.1016/0168-1923(91)90081-Z.
- Cochran, W.G. 1977. Sampling techniques. John Wiley & Sons, New York.
- Delaney, M.T., Fernandez, I.J., Simmons, J.A., and Briggs, R.D. 1996. Red maple and white pine litter quality: initial changes with decomposition. *Maine Agric. For. Exp. Stn. Tech. Bull.* 162.
- de Vries, P.G. 1986. Sampling theory for forest inventory. Springer-Verlag, New York.
- Finotti, R., Freitas, S.R., Cerqueira, R., and Vieira, M.V. 2003. A method to determine the minimum number of samples in litterfall studies. *Biotropica*, **35**: 419–421.
- Finzi, A.C., Van Breemen, N., and Canham, C.D. 1998. Canopy tree–soil interactions within temperate forests: species effects on soil carbon and nitrogen. *Ecol. Appl.* **8**: 440–446. doi:10.2307/2641083.
- Fule, P.Z., and Covington, W.W. 1994. Double sampling increases the efficiency of forest floor inventories for Arizona ponderosa pine forests. *Int. J. Wildland Fire*, **4**: 3–10. doi:10.1071/WF9940003.
- Gregoire, T.G., Valentine, H.T., and Furnival, G.M. 1995. Sampling methods to estimate foliage and other characteristics of individual trees. *Ecology*, **76**: 1181–1194. doi:10.2307/1940925.
- Innes, J.C. 2001. Size–density metrics, leaf area and productivity in eastern white pine. M.Sc. thesis, University of New Hampshire, Durham, N.H.
- Innes, J.C., Ducey, M.J., Gove, J.H., Leak, W.B., and Barrett, J.P. 2005. Size–density metrics, leaf area, and productivity in eastern white pine. *Can. J. For. Res.* **35**: 2469–2478. doi:10.1139/x05-174.
- Magill, A.H., and Aber, J.D. 1998. Long-term effects of experimental nitrogen additions on foliar litter decay and humus formation in forest ecosystems. *Plant Soil*, **203**: 301–311. doi:10.1023/A:1004367000041.
- Neumann, H.H., Hartog, G.D., and Shaw, R.H. 1989. Leaf area measurements based on hemispheric photographs and leaf-litter collection in a deciduous forest during autumn leaf-fall. *Agric. For. Meteorol.* **45**: 325–345. doi:10.1016/0168-1923(89)90052-X.
- Oderwald, R.G., and Jones, E. 1992. Sample sizes for point, double sampling. *Can. J. For. Res.* **22**: 980–983.
- Proctor, J. 1983. Tropical forest litterfall. I. Problems of data comparison. In *Tropical rain forest ecology and management*. Edited by S.L. Sutton, T.C. Whitmore, and A.C. Chadwick. Blackwell Scientific, Oxford, UK. pp. 267–273.
- Ringvall, A., Ståhl, G., Teichmann, V., Gove, J.H., and Ducey, M.J. 2001. Two-phase approaches to point and transect relascope sampling of downed logs. *Can. J. For. Res.* **31**: 971–977. doi:10.1139/cjfr-31-6-971.
- Shiver, B.D., and Borders, B.E. 1996. Sampling techniques for forest resource inventory. John Wiley & Sons, New York.
- Stocker, G.C., Thompson, W.A., Irvine, A.K., Fitzsimon, J.D., and Thomas, P.R. 1995. Annual patterns of litterfall in lowland and tableland rainforest in tropical Australia. *Biotropica*, **27**: 412–420. doi:10.2307/2388952.
- Sukhatme, P.V., and Sukhatme, B.V. 1970. Sampling theory of surveys with applications. Iowa State University Press, Ames, Iowa.
- Thompson, S.K. 1992. Sampling. John Wiley & Sons, New York.
- Williams, M.S. 2001. Comparison of estimation techniques for a forest inventory in which double sampling for stratification is used. *For. Sci.* **47**: 563–576.